Fermi National Accelerator Laboratory

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Observation of Excited Charmed Mesons*

The Tagged Photon Spectrometer Collaboration

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ABSTRACT

Using the Tagged Photon Spectrometer and a high energy photon beam, we have searched for excited states of charm in Fermilab experiment E691. We have found evidence for a state of mass 2459 ± 3 (stat) ± 2 (syst) MeV/c^2 and width $20 \pm 10 \pm 5$ MeV/c^2 which decays to $D^+\pi^-$. The fraction of D^+ coming from $D^{**o}(2459)$ is $.07 \pm .02 \pm .02$. We also confirm the $D^{**o}(2420) \rightarrow D^{*+}\pi^-$ decay observed previously in e^+e^- experiments and present evidence for its charged counterpart.

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While the S-wave charmed mesons, the D, D^*, D_s, and D_s^*, are well established, it has proved more difficult to detect charm states with $L > 0$. There should be four $L = 1$ states (the D^{**} states) having spin-parities (J^P) of 0^+, 1^+, 1^+, and 2^+. Many models have been put forward predicting the masses and widths of these states.[1] The mass values give information on the spin structure of the quark-antiquark potential at relatively long distances. The 2^+ can decay to both $D^*\pi$ and $D\pi$ while, because of spin-parity constraints, the 1^+ states can only decay to $D^*\pi$ and the 0^+ to $D\pi$. Although the predicted mass of the 2^+ varies from 2.3 to 2.5 GeV/c^2, all the models contend that the 2^+ is at least 100 MeV/c^2 more massive than the 0^+. Hence, the $D\pi$ channel is attractive because the 2^+ should be well isolated. The ARGUS and CLEO collaborations have previously reported on a candidate state at a mass of about 2420 MeV/c^2 decaying to $D^{*+}\pi^-$,[2-4] but, since its spin could not be unambiguously determined, this state could be either the 2^+, either of the 1^+'s, or some combination of all three. In this paper we report on signals found in the $D^+\pi^-$, $D^{*+}\pi^-$, and $D^o\pi^+$ channels using the full data set from E691. (The charge conjugate states are implicitly included throughout the paper).

The D signals are culled from the $\sim 10^8$ events written to tape during experiment E691. The data were collected using a photon beam of mean energy 145 GeV and the Tagged Photon Spectrometer. The spectrometer has been described in detail elsewhere.[5] The elements of the spectrometer most relevant for this analysis are the 35 drift chamber planes and two magnets for tracking and momentum resolution, the two threshold Čerenkov counters for particle identification, and the silicon microstrip vertex detector for high resolution tracking near the interaction point.

Our sample of D^{*+} decaying to $D^o\pi^+$ is used to search for the previously reported $D^{**o}(2420) \to D^{*+}\pi^-$ mode. The D^o is observed in both the $K^-\pi^+$ and $K^-\pi^+\pi^+\pi^-$ channels. The criteria for selecting D and D^* signals have been described elsewhere.[5,6] The actual values of the cuts used in this paper were chosen so as to maximize $S/\sqrt{B}$ where S is the number of Monte Carlo generated D^{**} events and B is the number of D^{**} background events (simulated using the wings of the data distributions). The final D^{*+} sample consists of 2908 ± 66 signal events over a background (within $\pm 2.5\sigma$ of the measured D^{*+} mass) of about 460 events.

The D^{*+} candidates are then combined with each π^- in the same event. The pions are required to have passed through both magnets for good momentum resolution and to have been identified as pions using the Čerenkov information. In addition, the distance of closest approach of the π^- and D^o momentum vectors is required to be less than 90 μm and the momentum of the $D^{*+}\pi^-$ state is required to be greater than 50 GeV/c. The resultant Δm plot (where $\Delta m = m(D^{*+}\pi^-) - m(D^{*+})$) is shown in Figure 1 where there is a significant effect around Δm of 420 MeV/c^2. The distribution is fitted using a function consisting of a background term of the form $(\Delta m - m_\pi)^\alpha e^{-\beta \Delta m}$, and a signal term whose form is that of a Breit-Wigner convoluted with a Gaussian resolution function. This background parameterization was found to describe well both the wrong sign (i.e., $D^{*+}\pi^+$) distribution and the distribution using the wings of the D^o. The experimental resolution is found using the Monte Carlo to be 8 MeV/c^2 (rms). We find 171^{+43}_{-58} events at a mass difference of 419 ± 8 MeV/c^2 and with a width of 58 ± 14 MeV/c^2. The χ^2 for the fit was 41.7 for 44 degrees of freedom and the statistical significance of the signal is 4 standard deviations. The mass is 2428 ± 8 MeV/c^2. Systematic errors of 5 MeV/c^2 in Δm and 10 MeV/c^2 in the width are estimated by observing the response of the signal to varied cuts and background shapes. The wrong sign and D^o wings distributions show no evidence of a similar enhancement.

The product of the efficiency for finding the π^- and the efficiencies of the distance of closest approach and D^{**o} momentum cuts is $(45 \pm 3)\%$. Using this and the numbers of D^{*+} and $D^{**o}(2420)$ events, we calculate the fraction of D^{*+} coming from $D^{**o}(2420)$ to be $.13^{+.03}_{-.04}$ (stat) $\pm .02$ (syst). The systematic error is dominated by the error in the background shape estimation. CLEO found this ratio to be $.12 \pm .04 \pm .03$ [4] and the most recent value from ARGUS is $.09^{+.03}_{-.02} \pm .03$.[3]

The D^+ is observed through its decay to $K^-\pi^+\pi^+$. The cuts were again chosen to maximize $S/\sqrt{B}$ but now using Monte Carlo generated $D^{**} \rightarrow D^+\pi^-$ events to simulate the signal and the wings of the D^+ for the background. The resulting $K^-\pi^+\pi^+$ mass spectrum is shown in Figure 2. There are 4135 ± 73 events in the peak over a background of approximately 740 events.

The D^+ candidates are then combined with each π^- in the same event. The pions are required to pass the same cuts as were used on the pions in the $D^{*+}\pi^-$ analysis except that there is no requirement on the momentum of the $D^+\pi^-$ state. The resulting $m(D^+\pi^-) - m(D^+)$ distribution is shown in Figure 3 where there is a clear peak at a mass difference (Δm) of around 590 MeV/c^2. The 'wrong sign' distribution (i.e., $D^+\pi^+$) and that obtained using the wings of the D^+ show no evidence of a similar enhancement. The background function used in the fit to the Δm plot contains two elements: an exponential to describe phase space, and a broad peak around 420 MeV/c^2 due to $D^{**o}(2420) \rightarrow D^{*+}\pi^-$ events where the D^{*+} decays to a D^+ and either a π^o or photon which goes undetected. The magnitude of this second contribution can be inferred from D^{*+} branching ratios and the measured D^{**o}/D^{*+} production ratio. The signal is fitted with a Breit-Wigner convoluted with a Gaussian resolution function. The resolution is found from the Monte Carlo to be 6.5 MeV/c^2. This fit gives 153^{+42}_{-37} events at a Δm of 590.7 ± 3.2 MeV/c^2 and a width of 20^{+11}_{-8} MeV/c^2. The peak has a statistical significance of 5 standard deviations and the χ^2 for the fit is 41.6 for 45 degrees of freedom. The corresponding mass for this state is 2459 ± 3 MeV/c^2. The parameters are relatively insensitive to the amount of $D^{*+}\pi^-$ feedthrough put into the fit. By observing changes in the signal due to varying background shapes and cuts, we estimate that the systematic error in Δm is 2 MeV/c^2 and in the width is 5 MeV/c^2. The product of the efficiencies for finding the π^- and of the distance of closest approach cut is $(56 \pm 3)\%$. Using this and the number of D^+ events, we find the fraction of D^+ coming from $D^{**o}(2459)$ to be $.07 \pm .02 \pm .02$.

It is expected that the 2^+ will be the narrowest and heaviest of the P-wave D mesons. Also, the other state which decays to $D^+\pi^-$, the 0^+, should be produced with a factor of five less cross section than the 2^+ due to spin multiplicity. While the fact that the state observed in the $D^+\pi^-$ spectrum is narrower and more massive than the $D^{*+}\pi^-$ state suggests that it might be the 2^+, there is no direct evidence for this. The statistics are also not good enough to measure the spin of the $D^{*+}\pi^-$ state from the angular distribution.

To search for the charged counterparts of the $D^{**o}(2459)$ and $D^{**o}(2420)$ we use D^o candidates which were found not to come from a D^{*+} (i.e., did not survive the m($D^o\pi^+$)-m(D^o) cut). The D^o is again observed in both the $K^-\pi^+$ and $K^-\pi^+\pi^+\pi^-$ channels. The invariant mass distribution combining both channels includes a signal of 4295 ± 81 events over a background of ~ 1550 events.

We estimate the size of the expected D^{**+} signals in the $D^o\pi^+$ spectrum as follows. Assuming the charged and neutral D^{**} states are produced equally, then isospin symmetry predicts that there should be equal numbers of $D^{**o} \rightarrow D^+\pi^-$ and $D^{**+} \rightarrow D^o\pi^+$ decays. However, the D^{*o} always decays to a D^o and a neutral (either a π^o or a photon) while less than half of D^{*+} decays are to $D^+ + neutral$.[7] A simple calculation using the D^*:D production ratio (which we have measured[8] to be consistent with the expected value of $3:1$) shows that about 80% of the reconstructed D^o events come from D^* decays as opposed to 60% in the D^+ case. Therefore, a 5σ effect in the $D^+\pi^-$ spectrum, combined with the fact that there is more background under the D^o than under the D^+, leads one to expect about a 2σ effect in the $D^o\pi^+$ spectrum, with roughly half the number of signal events as in the $D^+\pi^-$ case. On the other hand, the feedthrough from $D^*\pi$ to $D\pi$ is expected to be greater in the $D^o\pi^+$ spectrum than in the $D^+\pi^-$ spectrum since more of the D^o signal comes from D^* decays.

The D^o candidates are combined with π^+'s in the same event that survived the same cuts as were used on the π^-'s in the $D^{*+}\pi^-$ analysis. The $m(D^o\pi^+) - m(D^o)$ plot is shown in Figure 4 where there is no clear evidence for the charged counterpart of the $D^{**o}(2459)$. However, there is a significant peak around a mass difference (Δm) of 430 MeV/c^2 due to $D^{**+} \rightarrow D^{*o}\pi^+$ decays (where the neutral from the $D^{*o} \rightarrow D^o + neutral$ decay goes undetected). The Δm spectrum is fitted with a function which consists of a background term of the form $(\Delta m - m_\pi)^\alpha e^{-\beta\Delta m}$ and a signal term which is a Breit-Wigner convoluted with a Gaussian resolution function. The resolution for the signal was found using Monte Carlo data to be 12 MeV/c^2. This is wider than for the $D^{*+}\pi^-$ peak because the missing neutral tends to smear out the signal. We find 190^{+77}_{-44} events at a mass difference of 434 ± 7 MeV/c^2 and a width of 41 ± 19 MeV/c^2. The statistical significance of the signal is 4 standard deviations. The corresponding mass is 2443 ± 7 MeV/c^2 and the systematic errors are estimated to be 5 MeV/c^2 in the mass and 8 MeV/c^2 in the width. The number of $D^{**+}(2443)$ candidates is consistent with the observed D^{**o}/D^{*+} production ratio.

To summarize, we observe a 5σ effect in the $D^+\pi^-$ decay channel at a mass of $2459 \pm 3 \pm 2$ MeV/c^2 and with a width of $20 \pm 10 \pm 5$ MeV/c^2. The fraction of D^+ coming from $D^{**o}(2459)$ is $.07 \pm .02 \pm .02$. We also see evidence for the $D^{**o}(2420)$ decaying to $D^{*+}\pi^-$ at a mass of $2428 \pm 8 \pm 5$ MeV/c^2 and a width of $58 \pm 14 \pm 10$ MeV/c^2. The fraction of D^{*+} coming from $D^{**o}(2420)$ is found to be $.13^{+.03}_{-.04} \pm .02$. Finally, we observe evidence for the D^{**+} decaying to $D^{*o}\pi^+$ with a mass and width of $2443 \pm 7 \pm 5$ MeV/c^2 and $41 \pm 19 \pm 8$ MeV/c^2, respectively.

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References

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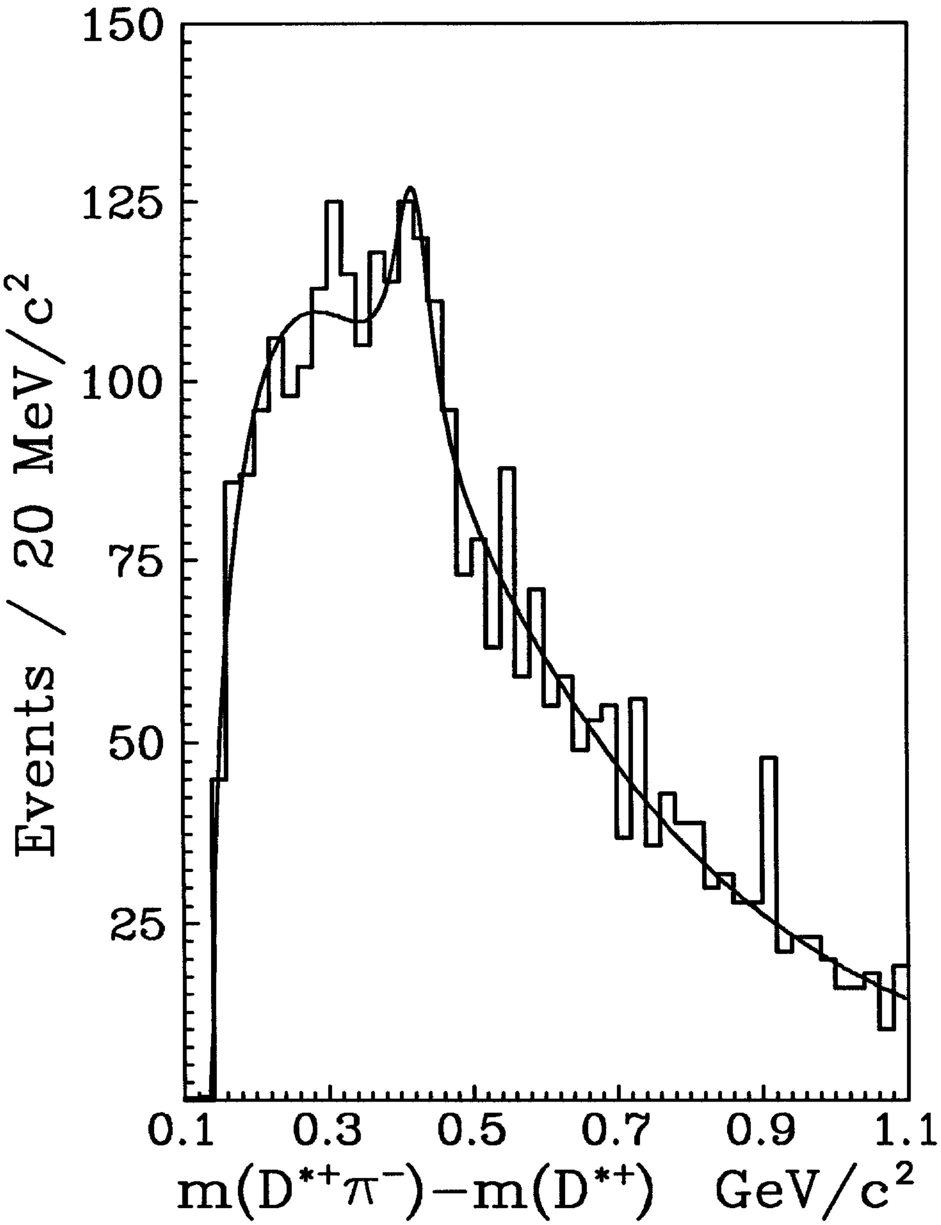
FIGURE CAPTIONS

FIG. 1. The $m(D^{*+}\pi^-) - m(D^{*+})$ plot showing the fit for the $D^{**o}(2420)$.

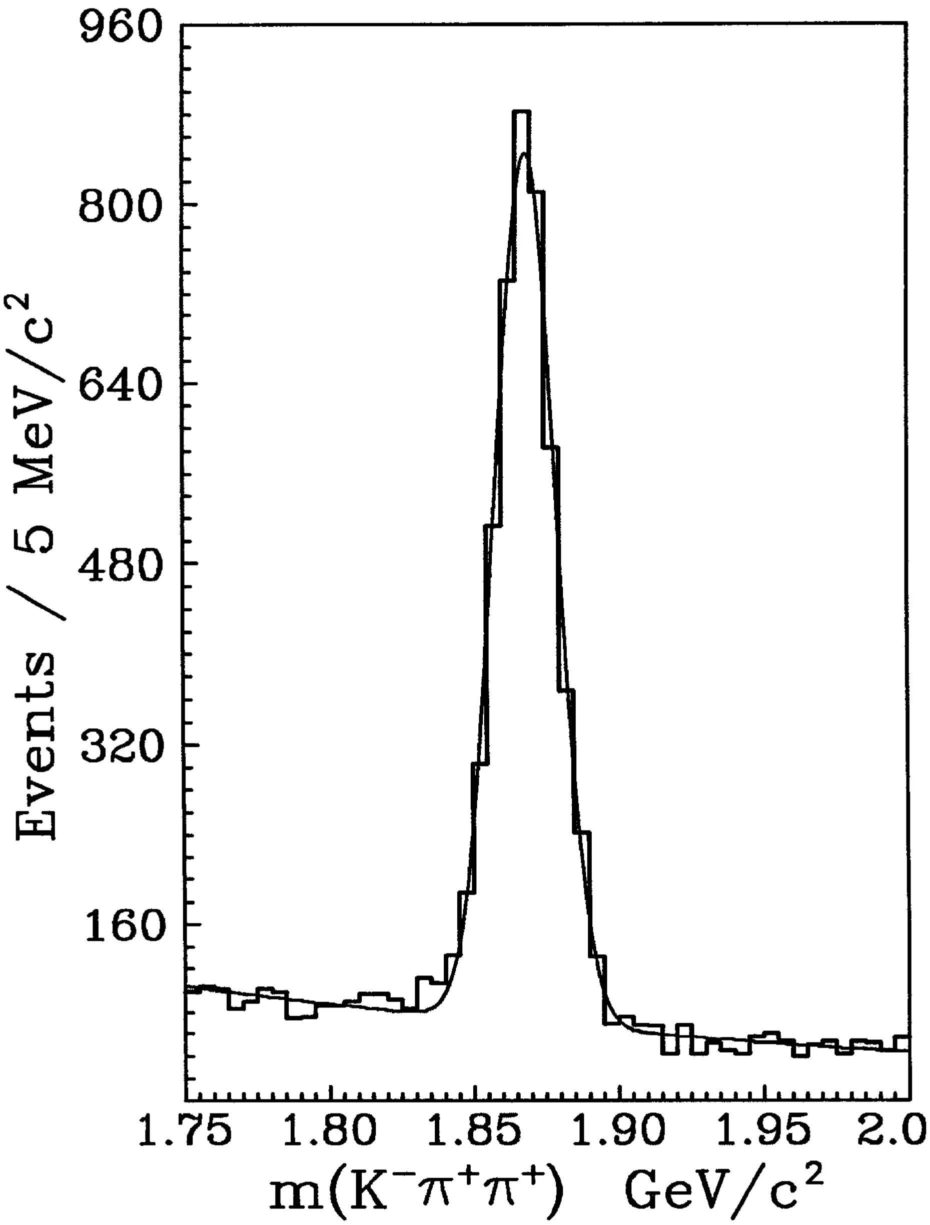
FIG. 2. The D^+ mass plot.

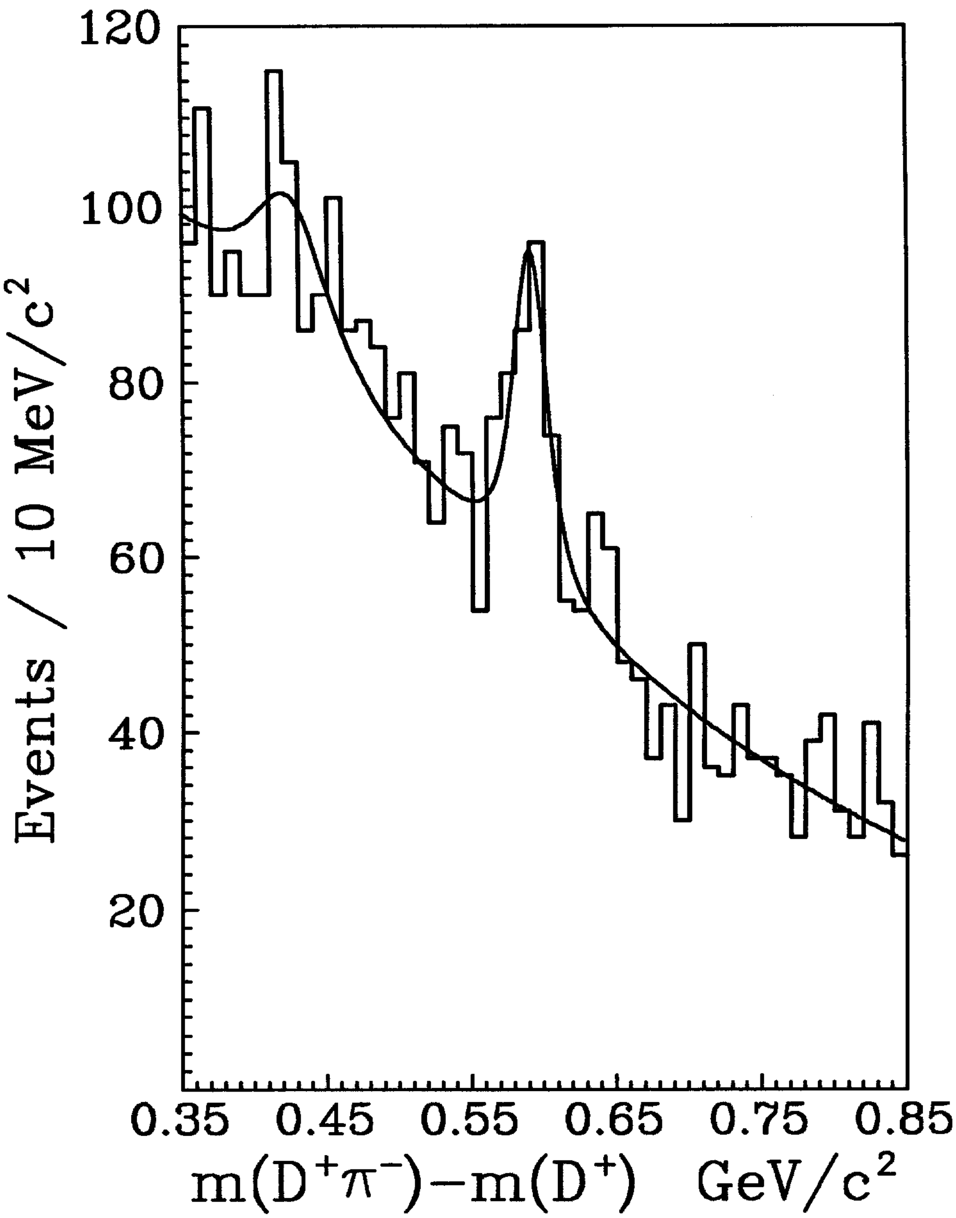
FIG. 3. The $m(D^+\pi^-) - m(D^+)$ plot showing the fit for the $D^{**o}(2459)$.

FIG. 4. The $m(D^o\pi^+) - m(D^o)$ plot showing the fit for the charged counterpart of the $D^{**o}(2420)$.

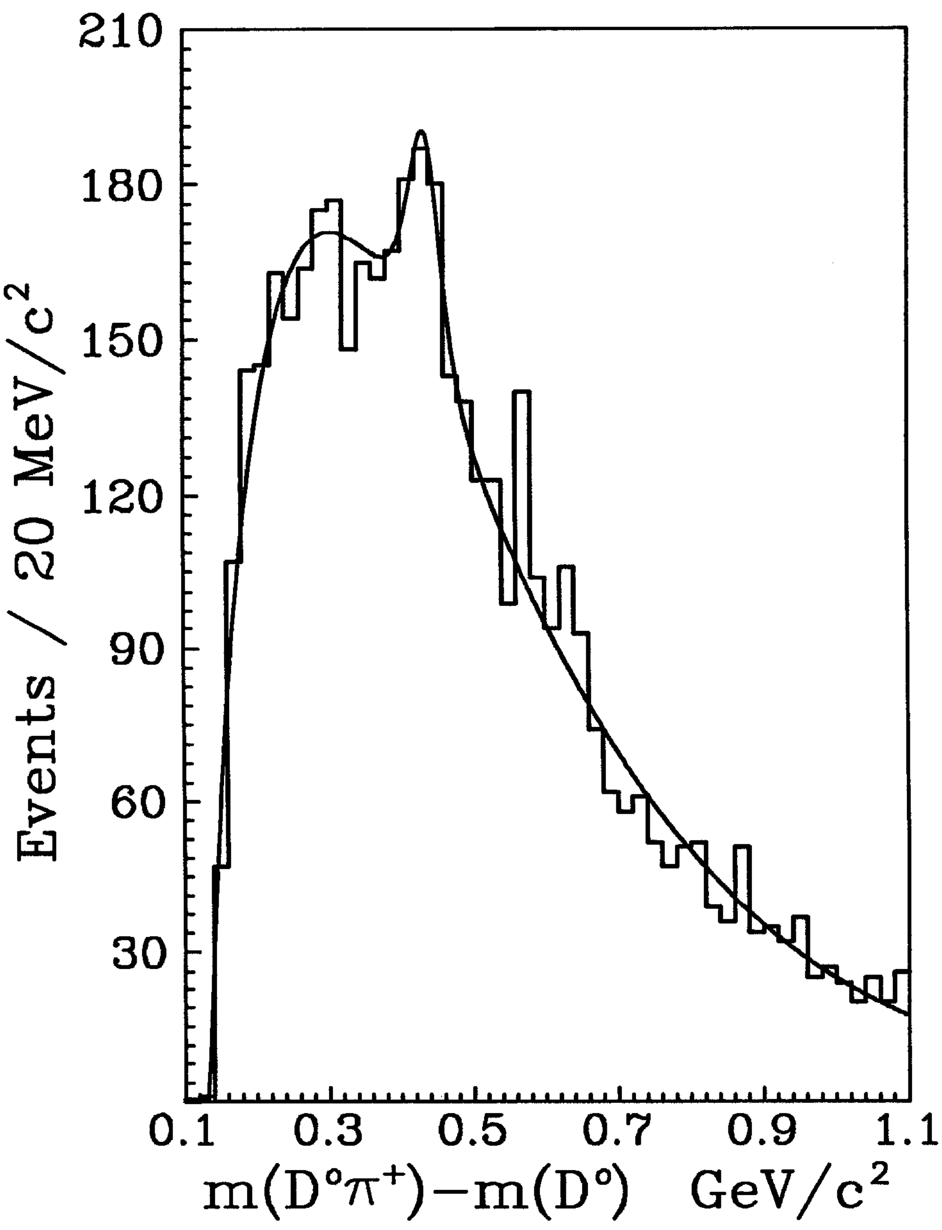


150
125
100
75
50
25
Events / 20 MeV/c^2
0.1
0.3
0.5
0.7
0.9
1.1
m(D$^{*+}\pi^-$)−m(D^{*+}) GeV/c^2


960
800
640
480
320
160
Events / 5 MeV/c^2
1.75
1.80
1.85
1.90
1.95
2.0
m($K^-\pi^+\pi^+$) GeV/c^2



120
100
80
60
40
20
Events / 10 MeV/c^2
0.35
0.45
0.55
0.65
0.75
0.85
m(D$^+\pi^-$)−m(D$^+$) GeV/c^2



210
180
150
120
90
60
30
Events / 20 MeV/c²
0.1
0.3
0.5
0.7
0.9
1.1
m(D°π⁺)−m(D°) GeV/c²